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Neutrino-cooled accretion and GRB variability

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Abstract. For accretion rates $\dot{M} \sim 0.1$ M$_\odot$/s to a few solar mass black hole the inner part of the disk is expected to make a transition from advection dominance to neutrino cooling. This transition is characterized by sharp changes of the disk properties. I argue here that during this transition, a modest increase of the accretion rate leads to powerful enhancement of the Poynting luminosity of the GRB flow and decrease of its baryon loading. These changes of the characteristics of the GRB flow translate into changing gamma-ray spectra from the photosphere of the flow. The photospheric interpretation of the GRB emission explains the observed narrowing of GRB pulses with increasing photon energy and the luminosity-spectral peak relation within and among bursts.

Key words. Gamma rays: bursts – Accretion, accretion disks

1. Introduction

The commonly assumed model for the central engine of gamma-ray bursts (hereafter GRBs) consists of a compact object, most likely a black hole, surrounded by a massive accretion disk. This configuration results naturally from the collapse of the core of a fast rotating, massive star (Woosley 1993; MacFadyen & Woosley 1999) or the coalescence of a neutron star-neutron star or a neutron star-black hole binary (for simulations see Ruffert et al. 1997).

The accretion rates needed to power a GRB are in the range $\dot{M} \sim 0.01 - 10$ M$_\odot$/s. Recently, much theoretical work has been done to understand the microphysics and the structure of the disk at this very high accretion-rate regime (e.g., Chen & Beloborodov 2007; hereafter CB07). These studies have shown that while for accretion rates $\dot{M} \ll 0.1$M$_\odot$/s the disk is advection dominated, when $\dot{M} \sim 0.1$M$_\odot$/s it makes a sharp transition to efficient neutrino cooling. This transition results to a thiner, much denser and neutron rich disk.

Here I show that, for reasonable scalings of the magnetic field strength with the properties of the inner disk, the advection dominance-neutrino cooling transition results in large changes in the Poynting flux output in the GRB flow. During this transition, a moderate increase of the accretion rate is accompanied by large increase of the Poynting luminosity and decrease of the baryon loading of the GRB flow. This leads to powerful and "clean" ejections of material. The photospheric emission from these ejections explains the observed narrowing of GRB pulses with increasing photon energy (Fenimore et al. 1995) and the luminosity-spectral peak relation within and among bursts (Liang et al. 2004).

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2. Disk transition to efficient neutrino cooling

In accretion powered GRB models the outflow responsible for the GRB is launched in the polar region of the black-hole-disk system. This can be done by neutrino-antineutrino annihilation and/or MHD mechanisms of energy extraction. In either case, the power output in the outflow critically depends on the physical properties of the inner part of the accretion disk. In this section, I focus on the disk properties around the transition from advection dominance to neutrino cooling. The implications of this transition on the energy output to the GRB flow are the topic of the next section.

Recent studies have explored the structure of accretion disks that surround a black hole of a few solar masses for accretion rates $\dot{M} \sim 0.01 - 10$ M$_\odot$/s. Most of these studies focus on 1-D "α"-disk models (where α relates the viscous stress to the pressure in the disk; Shakura & Sunyaev 1973) and put emphasis on the treatment of the microphysics of the disks connected to the neutrino emission and opacity, nuclear composition and electron degeneracy (Di Matteo et al. 2002; Korhi & Mineshige 2002; Kohri et al. 2005; CB07; Kawanaka & Mineshige 2007; hereafter KM07) and on general relativistic effects on the hydrodynamics (Popham et al. 1999; Pruet at al. 2003; CB07).

These studies have shown that for $\dot{M} \lesssim 0.1$ M$_\odot$/s and viscosity parameter $\alpha \sim 0.1$ the disk is advection dominated since the large densities do not allow for photons to escape. The temperature at the inner parts of the disk is $T \gtrsim 1$ MeV and the density $\rho \sim 10^8$ gr/cm^3 which results in a disk filled with mildly degenerate pairs. In this regime of temperatures and densities the nucleons have dissociated and the disk consists of free protons and neutrons of roughly equal number. The pressure in the disk is: $P = P_{\gamma,e^\pm} + P_{\rm b}$. The first term accounts for the pressure coming from radiation *and* pairs and the second for that

of the baryons. In the advection dominated regime the pressure is dominated by the "light particle" contribution (i.e. the first term in the last expression).

For accretion rates $\dot{M} \sim 0.1$ M$_\odot$/s, a rather sharp transition takes place in the inner parts of the disk. During this transition, the mean electron energy is high enough for electron capture by protons to be possible: $e^- + p \rightarrow n + \nu$. As a result, the disk becomes neutron rich, enters a phase of efficient neutrino cooling and becomes thinner. The baryon density of the disk increases dramatically and the total pressure is dominated by the baryon pressure. After the transition is completed the neutron-to-proton ratio in the disk is $\sim$ 10. Hereafter, I refer to this transition as "neutronization" transition.

The neutronization transition takes place at an approximately constant disk temperature $T \approx$ several$\times 10^{10}$ K and is completed for a moderate increase of the accretion rate by a factor of $\approx 2-3$. During the transition the baryon density increases by ≈ 1.5 orders of magnitude and the disk pressure by a factor of several (see CB07; KM07).

2.1. Scalings of the disk properties with $\dot{M}$

Although the numbers quoted in the previous section hold quite generally, the range of accretion rates for which the neutronization transition takes place depends on the α viscosity parameter and on the spin of the black hole. For more quantitative statements to be made, I extract some physical quantities of the disk before and after transition from Figs. 13-15 of CB07 for disk viscosity $\alpha = 0.1$ and spin parameter of the black hole $a = 0.95$. I focus at a fixed radius close to the inner edge of the disk (for convenience, I choose $r = 6GM/c^2$). The quantities before and after the transition are marked with the superscripts "A" and "N" and stand for Advection dominance and Neutrino cooling respectively. At $\dot{M}^{\rm A} = 0.03$ M$_\odot$/s, the density of the disk is $\rho^{\rm A} \simeq 3\cdot 10^9$gr/cm^3 and has similar number of protons and neutrons, while at $\dot{M}^{\rm N} = 0.07$ M$_\odot$/s, the density is $\rho^{\rm N} \simeq 9\cdot 10^{10}$gr/cm^3 and the neutron-to-proton ratio is $\sim$ 10. The temperature remains approximately constant for this range of accretion rates at $T \simeq 5\cdot 10^{10}$ K. A factor of $\dot{M}^{\rm N}/\dot{M}^{\rm A} \simeq 2.3$ increase in the accretion rate in this specific example leads to the transition from advection dominance to neutrino cooling.

Around the transition the (mildly degenerate) pairs contribute a factor of ~ 2 more to the pressure w.r.t. radiation. The total pressure is: $P = P_{\gamma,e^\pm} + P_{\rm b} \approx a_{\rm r}T^4 + \rho k_{\rm B}T/m_{\rm p}$, where $a_{\rm r}$ and $k_{\rm B}$ are the radiation and Boltzmann constants respectively (Beloborodov 2003; CB07). Using the last expression, the disk pressure before the transition is found: $P^{\rm A} \simeq 6\cdot 10^{28}$ erg/cm^3; dominated by the contribution of light particles as expected for an advection dominated disk. At the higher accretion rate $\dot{M}^{\rm N}$, one finds for the pressure of the disk $P^{\rm N} \simeq 4\cdot 10^{29}$ erg/cm^3. Now the disk is baryon pressure supported.

From the previous exercise one gets *indicative* scalings for the dependence of quantities in the disk as a function of $\dot{M}$ *during* the neutronization transition: $\rho \propto \dot{M}^4$ and $P \propto \dot{M}^{2.3}$. Doubling of the accretion rate during the transition leads to a factor of ~ 16 and ~ 5 increase of the density and pressure of the disk respectively.

Similar estimates for the dependence of the disk density and pressure on the accretion rate can be done when the inner disk is in the advection dominance and neutrino cooling regime but fairly close to the transition. In these regimes, I estimate that $\rho \propto P \propto \dot{M}$ (see, for example Figs. 1-3 in KM07).

Does this sharp change of the disk properties associated with the neutronization transition affect the rate of energy release in the polar region of the disk where the GRB flow is expected to form? The answer depends on the mechanism responsible for the energy release.

3. Changes in the GRB flow from the neutronization transition

Gravitational energy released by the accretion of matter to the black hole can be tapped by neutrino-antineutrino annihilation or via MHD mechanisms and power the outflow responsible for the GRB. We consider both of these energy extraction mechanisms in turn.

The neutrino luminosity of the disk just after the neutronization transition is of the order of $L_\nu \sim 10^{52}$ erg/s and consists of neutrinos and antineutrinos of all flavors. The fraction of these neutrinos that annihilate and power the GRB flow depends on their spatial emission distribution which, in turn, depends critically on the disk microphysics. For $\dot{M} \sim 0.1$M$_\odot$/s, this fraction is of the order of $\sim 10^{-3}$ (Liu et al. 2007), powering an outflow of $L_{\nu\bar{\nu}} \sim 10^{49}$ erg/s; most likely too weak to explain a cosmological GRB. The efficiency of the neutrino-antineutrino annihilation mechanism can be much higher for accretion rates $\dot{M} \gtrsim 1$M$_\odot$/s (e.g., Liu et al. 2007; Birkl et al. 2007) which are not considered here.

The second possibility is that energy is extracted by strong magnetic fields that thread the inner part of the disk (Blandford & Payne 1982) or the rotating black hole (Blandford & Znajek 1977) launching a Poynting-flux dominated flow. The Blandford-Znajek power output can be estimated to be (e.g. Popham et al. 1999)

$$L_{\rm BJ} \approx 10^{50} a^2 B_{15}^2 M_3^2 \quad \text{erg/s}, \tag{1}$$

where $B = 10^{15}B_{15}$ Gauss and $M = 3M_3$M$_\odot$. taking into account that magnetic fields of similar strength are expected to thread the inner parts of the disk, the Poynting luminosity output from the disk is rather higher than $L_{\rm BJ}$ because of the larger effective surface of the disk (Livio et al. 1999). In conclusion, magnetic field strengths in the inner disk of the order of $B \sim 10^{15}$ erg/s are likely sufficient to power a GRB via MHD mechanisms of energy extraction.

3.1. Luminosity and baryon loading of the GRB flow as functions of $\dot{M}$

In this section, I estimate the Poynting luminosity of the GRB flow for different assumptions on the magnetic field-disk coupling. The mass flux in the GRB flow is harder to constrain since it depends on the disk structure and the magnetic field geometry on the disk's surface. During the neutronization transition, the disk becomes thinner and, hence, more bound gravitationally. One can thus expect that a smaller fraction of $\dot{M}$ is

injected in the outflow. Here, I make the, rather conservative, assumption that throughout the transition, the mass flux in the outflow is a fixed fraction of accretion rate $\dot{M}$.

How is the magnetic field strength related to the properties of the disk? The magneto-rotational instability (hereafter MRI; see Balbus & Hawley 1998 for a review) can amplify magnetic field with energy density up to a fraction ϵ of the pressure in the disk. This provides an estimate for the magnetic field: $B^2_{\rm MRI} = 8\pi\epsilon P$. This scaling leads to magnetic field strength of the order of $\sim 10^{15}$ Gauss for the fiducial values of the pressure presented in the previous Sect. and for $\epsilon \simeq 0.2$.

The Poynting luminosity scales as $L_{\rm p} \propto B^2_{\rm MRI} \propto P \propto \dot{M}^{2.3}$ with the accretion rate during the neutronization transition (see previous Sect.). This leads to a rather large increase of the luminosity of the GRB flow by a factor of ~ 7 for a moderate increase of the accretion rate by a factor of $\simeq 2.3$. Furthermore, if we assume that a fixed fraction of the accreting gas is channeled to the outflow, then the baryon loading of the Poynting-flux dominated flow scales as $\eta \propto L_{\rm p}/\dot{M} \propto \dot{M}^{1.3}$. This means that during the transition the outflow becomes "cleaner" decreasing its baryon loading by a factor of ~ 3.

The disk can support large-scale fields more powerful that those generated by MRI. These fields may have been advected with the matter during the core collapse of the star (or the binary coalescence) or are captured by the disk in the form a magnetic islands and brought in the inner parts of the disk (Spruit & Uzdensky 2005). These large scale fields can arguably provide much more promising conditions to launch a large scale jet.

Stehle & Spruit (2001) have shown that a disk threaded by a large scale field becomes violently unstable once the radial tension force of the field contributes substantially against gravity. This instability is suppressed if the radial tension force is a faction $\delta \sim$ a few % of the gravitational attraction. Large-scale magnetic fields with strength: $B^2_{\rm LS} = \delta 8\pi\rho c_s v_k \propto (\rho P)^{1/2}$ can be supported over the duration of a GRB for $\delta \sim$ a few %. In the last expression $c_s = \sqrt{P/\rho}$ stands for the sound speed and v_k is the Keplerian velocity at the inner boundary.

The last estimate suggests that large scale field strong enough to power a GRB can be supported by the disk. The output Poynting luminosity scales, in this case , as $L_{\rm p} \propto B^2_{\rm LS} \propto (\rho P)^{1/2}$. During the neutronization transition, the Poynting luminosity increases steeply as a function of the accretion rate: $L_{\rm p} \propto (\rho P)^{1/2} \propto \dot{M}^{3.2}$. This translates to a factor of ~ 15 increase of the luminosity of the jet for a modest increase by ~ 2.3 of the accretion rate. Assuming that the rate of ejection of material in the GRB flow is proportional to the mass accretion rate, the baryon loading of the flow is found to decrease by a factor of ~ 6 during the transition (since $\eta \propto L_{\rm p}/\dot{M} \propto \dot{M}^{2.2}$).

Before and after the transition the disk is advection dominated and neutrino cooled respectively. When the disk is in either of these regimes the disk density and pressure scale roughly linearly with the accretion rate (at least for accretion rates fairly close to the neutronization transition; see previous Sect.), leading to $L_{\rm p} \propto \dot{M}$ and $\eta \sim$ constant. The Poynting luminosity and the baryon loading of the GRB flow around the neutronization transition are summarized by Fig. 1.

Although the Poynting flux output depends on assumptions on the scaling of the magnetic field with the disk properties,

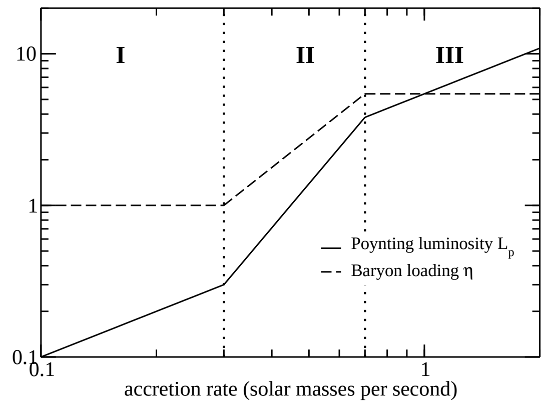

Fig. 1. Poynting luminosity and baryon loading (both in arbitrary units) of the GRB flow around the neutronization transition of the inner disk. In regions marked with I and III the inner disk is advection and neutrino cooling dominated respectively. In region II, the neutronization transition takes place. During the transition, the Poynting luminosity increases steeply with the accretion rate while the baryon loading of the flow is reduced (i.e. η increases).

the neutronization transition generally leads to steep increase of the Poynting luminosity as function of the accretion rate and to a "cleaner" (i.e. less baryon loaded) flow. Observational implications of the transition are discussed in the next section.

4. Connection to observations

The mechanism I discuss here operates for accretion rates around the neutronization transition of the inner disk and provides the means by which modest variations in the accretion rate give magnified variability in the Poynting flux output and baryon loading of the GRB flow. Since the transition takes place at $\dot{M} \sim 0.1\ M_\odot$/s which is close to the accretion rates expected for the collapsar model (MacFadyen & Woosley 1999), it is particularly relevant for that model. To connect the flow variability to the observed properties of the prompt emission, one has to assume a model for the prompt emission. Here we discuss internal shock and photospheric models.

Episodes of rapid increase of the luminosity of the flow can be viewed as the ejection of a distinct shells of material. These shells can collide with each other further out in the flow leading to internal shocks that power the prompt GRB emission (Rees & Mészáros 1994). For the internal shocks to be efficient in dissipating energy, there must be a substantial variation of the baryon loading among shells. This may be achieved, in the context of the model presented here, if the accretion rate, at which the neutronization transition takes place, changes during the evolution of the burst. The accretion rate at the transition decreases, for example, with increasing spin of the black hole (CB07). Since the black hole is expected to be substantially span up because of accretion of matter during the evolution of the burst (e.g. MacFadyen & Woosley 1999), there is the possi-

bility, though speculative at this level, that this leads to ejection of shells with varying baryon loading.

4.1. Photospheric emission

Photospheric models for the origin of the prompt emission have been recently explored for both fireballs (Mészáros & Rees 2000; Ryde 2004; Rees & Mészáros 2005; Pe'er et al. 2006) and Poynting-flux dominated flows (Giannios 2006; Giannios & Spruit 2007; hereafter GS07). Here, I focus mainly to the photosphere of a Poynting-flux dominated flow since it is directly applicable to this work.

In the photospheric model, the observed variability of the prompt emission is direct manifestation of the central engine activity. Modulations of the luminosity and baryon loading of the GRB flow result in modulations of the location of the photosphere of the flow and of the strength and the spectrum of the photospheric emission (Giannios 2006; GS07). In particular, in GS07 it is demonstrated that *if* the increase of the luminosity of the flow is accompanied by decrease of the baryon loading such that[1] $\eta \propto L^{0.6}$, the photospheric model can explain the observed narrowing of the width of the GRB pulses with increasing photon energy reported by Fenimore et al. (1995). The same η-L scaling also leads to the photospheric luminosity scaling with the peak of the $\nu \cdot f(\nu)$ spectrum as $L_{\rm ph} \propto E_{\rm p}^2$ *during* the burst evolution in agreement with observations (Liang et al. 2004).

The simple model for the connection of the GRB flow to the properties of the central engine presented here predicts that $L \propto \dot{M}^{2.3...3.2}$ and $\eta \propto \dot{M}^{1.3...2.2}$ during the neutronization transition. The range in the exponents comes from the different assumptions on the disk-magnetic field connection (see Sect. 3). This translates to $\eta \propto L^{0.6...0.7}$ which is very close that assumed by GS07 to explain the observed spectral and temporal properties of the GRB light curves.

Although the launched flow is Poynting-flux dominated, it is conceivable that it undergoes an initial phase of rapid magnetic dissipation resulting to a fireball. The photospheric luminosity and the observed temperature of fireballs scale as $L_{\rm ph} \propto \eta^{8/3} L^{1/3}$, $T_{\rm obs} \propto \eta^{8/3} L^{-5/12}$ respectively (Mészáros & Rees 2000). Using the scaling $\eta \propto L^{0.6...0.7}$ found in this work and identifying the peak of the photospheric component with the peak of the emission $E_{\rm p}$ one finds that $L_{\rm ph} \propto L^{1.9...2.2}$ and $E_{\rm p} \propto L^{1.2...1.4}$. The last scalings suggest that the photospheric emission from a fireball can further enhance variations in the gamma-ray luminosity while $L_{\rm ph}$ and $E_{\rm p}$ follow the Liang et al. relation. Still dissipative processes have to be considered in the fireball so that to explain the observed non-thermal spectra.

5. Conclusions

In this work, a mechanism is proposed by which moderate changes of the accretion rate at around $\dot{M} \sim 0.1\ M_\odot$/s to a few solar mass black hole can give powerful energy release episodes to the GRB flow. This mechanism is directly applicable to the collapsar scenario for GRBs (Woosley; MacFadyen & Woosley 1999) and can explain how moderate changes in the accretion rate result in extremely variable GRB light curves.

This mechanism operates when the inner part of the accretion disk makes the transition from advection dominance to neutrino cooling. This, rather sharp, transition is accompanied by steep increase of the density and the pressure in the disk (CB07; KM07). This leads to substantial increase of the magnetic field strength in the vicinity of the black hole and consequently boosts the Poynting luminosity of the GRB flow by a factor of $\sim 7-15$. At the same time, assuming that the ejection rate of material scales linearly with the accretion rate, the baryon loading of the flow *decreases* by a factor $\sim 3-6$. This results in a luminosity-baryon loading anticorrelation.

The changes of the characteristics of the GRB flow can be directly observed as modulations of the photospheric emission giving birth to pulses with spectral and temporal properties similar to the observed ones (GS07). The photospheric interpretation of the prompt emission is in agreement with the observed narrowing of the pulses with increasing photon energy (Fenimore et al. 1995) and the luminosity-peak energy correlation during the evolution of GRBs (Liang et al 2004). The Amati relation (Amati et al. 2002) is possibly result of the fact that more luminous bursts are on average less baryon loaded.

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[1] In GS07, the parameterization of the baryon loading of the flow is done by the magnetization σ_0 that is related to η through $\eta = \sigma_0^{3/2}$.